Fracture Critical Members Revisited

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OTEC
October 2, 2018
Current Fracture Control Plan

• Today the FCP is fragmented in the US Bridge industry
  • Material & Design
  • Fabrication/shop inspection
  • Field Inspection

• In a “True” FCP these are integrated
  • Shortfalls in one area can be made up in others
  • e.g., 24 month interval is not linked to crack tolerance
    • What if something bad happens after the inspector leaves?
Current Fracture Control Plan

- Further, meeting the modern Fracture Control Plan offers no relief
  - i.e., In-service inspection unaffected

1950s field welded steel bridge carrying ADTT 15,000 with E’ flange details

New bridge w/ HPS, HOV, bridge highly fatigue resistance fabricated to FCP
### BRIDGES WHERE FRACTURES OCCURRED

<table>
<thead>
<tr>
<th>BRIDGE</th>
<th>CAUSE</th>
<th>DO WE ALLOW THIS TODAY?</th>
<th>WOULD FIELD INSPECTION HAVE PREVENTED</th>
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More things to keep in mind...

• We perform hands-on inspection for safety...or so we think

• Recent INDOT study found the following:
  • The congested crash rate on all Indiana interstates in 2014 was found to be 24 times greater after 5 min. of queue
  • What about highway worker safety?
• We hope to find cracks before they are an issue
  • What about POD?
    • Existing data not very encouraging
    • Are we able to find what we think we can find?
Actual POD Might Surprise You

Crack tolerance of member should be linked to inspection capability... (seems like a good idea)
Three Major Research Projects to Reevaluate the Concept of the FCM

- Exploiting internal redundancy – TPF-5(253)
- Exploiting advanced system analysis – NCHRP Report 883
- Exploiting superior toughness of HPS – TPF-5(238)

Resulted in Two new Guides Specs. (Approved in June 2018)

“AASHTO Guide Specifications for Internal Redundancy of Mechanically-fastened Built-up Steel Members”
“AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members”
INTERNAL REDUNDANCY RESEARCH

TPF-5(253)
Experimental Program – Fracture Testing

- Notch a component
  - Controlled location (angle/cover plate)
    - Not looking at initial fatigue life – already documented
    - Crack growth through fatigue to critical length (LEFM)
- Cool beam → ensured lower shelf behavior
  - Warmest was -60F….some as cold as -120F
  - Eliminates “but you had good steel” comment
- Apply load to induce a fracture
  - And then….nothing happened
  - Needed to drive a “wedge” into the crack!!
Experimental Testing

TPF 5(253)
Member-level Redundancy of Built-up Steel Girders

Purdue University

PI - Robert Connor
Graduate Research Assistant - Matt Hebdon
Large-Scale Tension Frame #2
Axial Member Fracture Tests
Fatigue Tests – What is after-fracture fatigue life?

- Followed fracture test
- Established fatigue life in the faulted state, i.e. one failed component
Analytical Parametric Studies

- Developed simple user-friendly evaluation tools
- Girders, multi-component, angle-only, and two-channel type members
SYSTEM ANALYSIS RESEARCH

NCHRP Project 12-87a
(Published as NCHRP Report 883)
Objective and Scope

• Develop a methodology to establish whether a member is an FCM or an SRM
  • 2012 FHWA Memo and now AASHTO LRFD define what an SRM “is”.
  • Recognizes that the outcome is to remove or alter hands-on inspection interval associated with FCMs

• Codify the methodology into stand-alone AASHTO Guide Specifications
Scope of NCHRP Project 12-87a

• Cover existing and structures under design (i.e., new)

• Applicable to entire steel bridge inventory
  • Within reason

• Analysis, load model, and failure criteria must be universal to wide-range of structure types, configurations, and failure modes
What other Criteria are needed for Classifying a Member as FCM, SRM, or IRM?

• For example:
  • What are the minimum damage scenarios?
  • What is/defines failure?
    • i.e., the bridge should be classified as having FCMs if....
  • What loading should be applied in the faulted state?
    • One HS-20....All lanes loaded with HL-93
  • What level of “refinement” in the refined analysis?
• Guidance provided on all of the above based on the research
SO WHAT’S IN THE GUIDE SPECIFICATIONS?
Some Fundamentals of the IRM Specification

• Existing members and new designs (riveted or bolted)
• Flexural and axial members
• Strength and fatigue criteria determine internal redundancy
• Provisions “keep you in a box” in terms of:
  • General criteria
  • Member proportions AND condition
  • Must have remaining fatigue life in “unfaulted condition”
    • Faulted condition = one component failed
Some Basics of the Specification

• Not all members will meet provisions
• Passing member classification: *Internally Redundant Member* (IRM)
• Easy application
  • Stress amplification of common stress calculations
  • Or addition of secondary moments
• Determine interval for “Special Inspection of IRMs”
  • Objective to identify broken components
  • Depth of Special Inspections determined by owner
  • Routine safety inspections are not changed
• **Not** intended to be used to justify leaving a broken component in place for extended period
Biggest Impact is Related to Inspection Intervals

- **Case I members:**
  Unfaulted fatigue life = infinite
  - 1a: Unfaulted = infinite & Faulted = infinite
  - 1b: Unfaulted = infinite & Faulted > 0
    - Calculate $Y_{REM}$ in faulted state (a.k.a., $N_f$)

- **Case II members:**
  0 < Unfaulted fatigue life < 25 years
  - $N_f = Y_f \left(1.0 - \frac{N_u}{Y_u}\right)$

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<th>Maximum Permitted Interval (Years)</th>
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<td>$N_f &lt; 20$</td>
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*The calculated inspection interval may be rounded up to the next even year interval.

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<td>$N_f \leq 5$</td>
<td>Smaller of 2 years or $0.5N_f^*$</td>
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<tr>
<td>5 &lt; $N_f &lt; 20$</td>
<td>$0.5N_f^{**}$</td>
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*The calculated inspection interval may be rounded up to the next half-year interval.
**The calculated inspection interval may be rounded up to the next even year interval.
Major Advantages of this Approach

• Much higher Probability of Detection (POD)
  • Inspection objectives different than “conventional” objectives
  • Damage detection capabilities on par with potential damage

More likely to find this

Than this
Features of the SRM Guide Spec

• Screening Criteria
• Analysis Requirements
• Load Model
• Performance Criteria
  • Strength and service
Basic Load Models to Evaluate Bridge in Faulted Condition

• Concluded there are two Load Combinations to be checked:
  • First - Failure event, referred to as **Redundancy I**
    • Includes dynamic inertial effects.
    • Point-in-time live load considered
  • Second - Post-failure service period, referred to as **Redundancy II**
    • Bridges that underwent failure of an FCM and did not collapse carried traffic afterwards
    • Different loading scenario
      • No dynamic fracture due to fracture
      • Longer exposure to live load
Resulting Load Combinations

 Structures built to FCP
  • $R_1 = (1 + D_{AR}) (1.05 \text{ DC} + 1.05 \text{ DW} + 0.85 \text{ LL})$
  • $R_{2**} = 1.05 \text{ DC} + 1.05 \text{ DW} + 1.30 (\text{LL} + \text{IM}^*)$

 Structures not built to FCP (less likely to fracture)
  • $R_1 = (1 + D_{AR}) (1.15 \text{ DC} + 1.25 \text{ DW} + 1.00 \text{ LL})$
  • $R_{2**} = 1.15 \text{ DC} + 1.25 \text{ DW} + 1.50 (\text{LL} + \text{IM}^*)$

*IM = 15% 
**R2 Applies to IRMS.
Applied Notional Live Load

• Use Existing HL-93
  • Represents reasonable envelope of live load effects
• Guide Specifications allow owner-specific live loads if need to address special needs
Example Application of NCRHP 883

- 21 different continuous twin tub bridges evaluated using NCHRP 883 criteria for the State of Wisconsin
Characteristics of the WisDOT Bridges

1) End span lengths: 100 ft. to 210 ft.
2) Continuous spans (2 to 7)
3) Composite design
4) Full-depth full-width diaphragms
5) Number of traffic lanes: one to two
6) Web height: 60 in. to 86 in.
7) Girder spacing: 16 ft. to 25 ft.
   • Between the center of the bottom flanges
8) Clear distance: 8 ft. to 13.875 ft.
   • Between the center of the interior top flanges
Results of the Study?

- ALL 21 bridges found to possess significant reserve strength with an entire tub girder fractured
- “Satisfied” NCHRP 883 criteria

CONCLUSION?

THE GIRDERS ARE NOT FCMs!!!
Results of the Study?

• Once enough structures are analyzed, can likely define a family of bridges that are not FC if “X, Y, and Z” are met
• “Deemed to Satisfy”

• Likely about 90% of the way there for continuous twin tubs
• Working to identify these characteristics
• Won’t require Non-linear FEA
CLOSING THOUGHTS

THE FUTURE OF THE CONCEPT OF FRACTURE CRITICAL???
Overall Objectives Moving Forward?

- If the fracture limit state is adequately addressed in some rational way, the term “FCM” has no meaning.

- For example, since we design for buckling, a non-redundant compression member is not referred to as “buckling critical”.
  - Why? We “believe” in design methods to address this limit state.

- Today, using state-of-the-practice, the risk associated with fracture can be treated like any other limit state.
  - Minimize risk and achieve desired reliability.
Other Industries Treat Redundancy in a Rational Way

- Two-winged aircraft are acceptable as RISK associated with failure is low
  - Consequence high
  - Likelihood low

- Modern steel bridges?
  - Likelihood low (FCP)
  - Consequence low (IRM/SRM)

We can fly on one wing!
Thank you.